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ABSTRACT

Impulse drying is an advanced technique currently being developed at the Institute of Paper Science and Technology (IPST), for removing water from paper during its manufacture. The objective of this study was to predict the lubrication flow characteristics and the performance of a crown-compensated (CC) press roll for various operating conditions. By generating mathematical expressions for various regions of the roll and the shoe, coupling the Hagen-Poiseuille equation for laminar flow through capillary tubes with the expressions for a viscous flow in a curved-wall channel, and balancing all forces and moments applied to the internal shoe, a system of nonlinear transcendental equations was produced and solved by a numerical scheme. A parametric study was performed to determine relative influence of lubricant viscosity on the predicted results, and it was determined that this variable had a profound effect on the performance of the press roll. The model predicted that operation of the press rolls at relatively higher loads will result in a more stable hydrostatic shoe, one in which the position of the shoe becomes relatively independent of the variation in theroll speed.

INTRODUCTION

Shown in figure 1 is a crown-compensated (CC) extended-nip press roll proposed for impulse drying of paper materials. This is a novel technique which is currently being developed at the Institute of Paper Science and Technology (IPST), for removing water from paper during its manufacture. Previous studies have demonstrated that implementation of impulse drying technique will result in significant energy savings, and improved paper properties [1-3]. The roll rotates counterclockwise, and an external force applied to the top of its internal hydrostatic shoe will cause a pressurized oil to be injected through a series of capillary tubes within the shoe to provide lubrication by producing an oil film between the bottom surface of the shoe and the inside surface of the roll (figure 2). The oil also acts as a heat sink for heat loss from the inner surface of the roll. Because of the forces applied to the shoe and the counterclockwise rotation of the roll, the shoe will have a vertical displacement and a clockwise rotation, and under a steady state condition, it will reach an equilibrium position. In the overall process, wet paper sheets transported on felt enter an extended nip at point A, (figure 1), and leave the nip at point C, while the roll itself is heated in a zone from point D to point E to achieve a prescribed roll surface temperature at the entrance to the nip at point A. The objective of this study was to predict the lubrication flow characteristics and the performance of a crown-compensated (CC) press roll using an analytical model, and, also, to perform a parametric study to determine relative influence of the oil viscosity on the magnitude of the predicted quantities.

DEVELOPMENT OF THE MODEL

To develop the analytical model it was assumed that the arcs describing the bottom of the shoe and the surface of the roll lie on circles of radii R_s and R, respectively (see the curves shown by dash-line in figure 3). The actual channel, with curved walls, was approximated by a planar walled convergent channel or wedge. The planar walled channel described above is formed by inscribing appropriate secant lines within the circles describing the bottom of the shoe and the inside of the roll. The internal shoe is loaded by an external force F, measured per unit cross machine direction width of the shoe (w_{sh}), so that the net load on the shoe is just F times the width of the shoe (w_{sh}). The other key variables which enter the mathematical model are p_{sh} (the pressure at the top of the shoe), p_{exit} (in this case $p_{exit} = p_{atm}$), $\tilde{R}_{eff}$ and $\tilde{l}_{eff}$ (respectively, the effective radius and length of each of the capillaries), ϕ (half of the angle subtended by those radii, in the circle describing the shoe, through the end points of the arc coincident with the bottom of the shoe), s (the linear speed of the inner surface of the roll) and μ and ρ (respectively, the viscosity and density of the lubricating oil which in this initial model they are assumed to be constant). As a consequence of the loading of the internal shoe, the pressure difference $p_{sh} - p_{exit}$, and the counterclockwise rotation of the roll, the shaft of the shoe will be displaced to the right. Then the middle rib at the top of this shaft comes into contact with the wall, and the shoe hits the wall of the confinement shaft; thereafter, the shoe will turn clockwise through an angle ψ (figure 3) and, also, execute a motion, normal to the plane of the incoming paper, until it achieves an equilibrium position. The equilibrium position may be completely specified by the two variables ψ and $d_0 = \overline{BB'}$. At a given tangential speed s of the roll, and a given load F on the shoe, the center of the circle describing the bottom surface of the shoe is located at the point $(a, R+b)$ where a, b are to be determined by a set of coupled, nonlinear equilibrium equations. The lubrication channel is formed by the arcs $\widehat{ABC}$ and $A'B'C'$ and a base lubrication thickness may be measured along the segment $\overline{BB'}$. An approximating planar-walled channel (or wedge) may be constructed by using the secant lines through the points A, C and A', C'.

By generating mathematical expressions for various regions of the roll and the shoe, coupling the Hagen-Poiseuille equation for laminar flow through capillary tubes with the expressions for a viscous flow in a curved-wall channel, and balancing all forces and moments applied to the internal shoe, a system of coupled nonlinear transcendental algebraic equations was produced and solved by numerical scheme. First ψ and d_0 were determined from the numerical solution, then the geometrical quantities as well as the pressures, mass flow rates, and the velocity fields in the subchannels for each operating condition were computed. A parametric study was performed to determine relative influence of the oil viscosity on the predicted values of lubricant thickness, mass flow rate, pressure, and mechanical power. The velocity fields are two-dimensional and are obtained by imposing the standard lubrication theory assumption (e.g., [4].[5]) of pseudo-plane Couette flow. Expressions for the tangential and normal forces exerted by the lubricating oil both on the bottom surface of the shoe as well as on the inside surface of the roll are also computed and these results are used to compute the net drag force acting on the roll and, thus, the energy required to operate the CC roll. In the right-hand subchannel, the expression for the velocity field is obtained from the following standard lubrication theory [4],[5]:

$$\bar{u}_R(x,y) = \frac{1}{2\mu}\bar{C}_R(x)y(d_R(x)-y)+s(1-yd_R^{-1}(x)) \quad (1)$$

with $\bar{C}_R(x) = -\bar{p}_{R'}(x)$ where, $l_\beta \leq x \leq L_\beta$, ($l_\beta$ and L_β are distances from the origin for the points located at the end of the right-hand recess and at the end of the right-hand subchannel), $d_R(x)$ is the channel thickness at a point, and y is the distance measured from the bottom to the top of the channel at any point along the channel. The velocity field $\bar{u}_R(x,y)$ satisfies $\bar{u}_R(x,0) = s$, and $\bar{u}_R(x,d_R(x)) = 0$ for all $x, l_\beta \leq x \leq L_\beta$. From this equation expressions for the mass flow rate/unit depth, and pressure distribution along the right-hand channel will be obtained in which the mass flow rate is independent of x, and the pressure, $\bar{p}_R(x)$, is independent of y. Let n_c denote the number of capillaries which feed lubricant into each of the two subchannels. Assuming Hagen-Poiseuille flow in the capillaries, which are idealized to be circular cylindrical tubes of length $\tilde{l}_{eff}$ and radius $\tilde{R}_{eff}$, the volume flow rate through any one of the n_c capillaries which feed lubricant in to the right-hand subchannel is:

$$\dot{q}_c^R = \pi\tilde{R}_{eff}^4(p_{sh}-\tilde{p}_R)/8\mu\tilde{l}_{eff} \quad (2)$$

Where, $p_{sh} - \tilde{p}_R$ is the pressure differential through a capillary. The pressure at the end of the channel is atmospheric. Relating this volume flow rate to the equation for the mass flow rate obtained by integrating the velocity profile (equation 1), the unknown recess pressure ($\tilde{p}_R$) will be eliminated an expression for the lubricant mass flow rate through the right-hand channel in terms of $p_{sh} - \tilde{p}_{atm}$ will be obtained. Similar calculations can be obtained for the left-hand channel. These calculations and detail mathematical expressions for other quantities are given in a previous study [6]. The expressions obtained for the velocity, and pressure fields will be used to compute the normal and tangential forces exerted by the lubricant, in both the right and left-hand subchannels, on the bottom surface of the shoe and the inside surface of the roll; the resulting expressions will then be used to set up the equilibrium equations which serve to determine ψ and d_0 in terms of the other parameters in the model. The normal forces exerted on the roll (shell) in those regions of the right subchannels which lie between the end of the sets of recesses in the right-hand subchannel and the end of that subchannel is computed as:

$$\bar{N}_{sl}^R = \int_{l_\beta}^{L_\beta}(\bar{p}_R(x)-\tilde{p}_R)dx \quad (3)$$

A force with the same magnitude but in the opposite direction will be exerted to the bottom surface of the shoe, thus, $\bar{N}_{sh}^R = -\bar{N}_{sl}^R$. For the tangential forces acting on the inside surface of the roll in the right-hand subchannel, the following relation is used:

$$\bar{T}_{sl}^R = -\mu\int_{l_\beta}^{L_\beta}\left(\frac{\partial\bar{u}_R}{\partial y}(x,y) \mid y=0\right)dx \quad (4)$$

The corresponding tangential force along the bottom surface of the shoe is computed from:

$$\bar{T}_{sh}^{R} =$$

$$- \mu \int_{l_\beta}^{L_\beta} \left(\frac{\partial \bar{u}_R}{\partial y}(x, y) \mid y = d_R(x) \right) dx \quad (5)$$

In order for the shoe to reach an equilibrium condition, all components of forces applied on the shoe along the horizontal, and vertical directions, as well as moment of forces about a point on the shoe (e.g., point B in figure 3) must be in balance, this results in three simultaneous equations. These three equations of equilibrium can be converted to two coupled nonlinear system of algebraic equations which serve to determine the variables d_0 and ψ in terms of the load F (applied at the top of the shaft of the shoe) the tangential speed of the roll (s), the pressure drop $p_{sh} - p_{atm}$, the geometry of the shoe, and the properties of the lubricant. After the values of ψ and d_0 were determined from the equilibrium equation, then all other unknown quantities such as the thickness of the channel at various locations, mass flow rates, pressure field, velocity field, as well as for all the normal and tangential forces which act along the bottom surface of the shoe, inside the recesses, and along the inside surface of the roll can be determined.

RESULTS AND DISCUSSION

In this section, the results for the case in which the roll and the shoe are machined to the same radius of 508.13 mm ($R_s = R =$ 20.005 in) will be presented. This shoe/roll was subjected to loads in the range of 175-1751 KN/m (1000-10,000 PLI) and roll speeds of 305-1067 m/min (100-3500 ft/min). The lubricant viscosity and density values were assumed to be 56 centipoise and 873 Kg/m^3, respectively. These properties correspond to an ISO 150 Mobil lubricant at a temperature of 57°C which was employed in operation of a smaller size press roll by the Beloit corporation for the small roll/shoe [6]. Since the speed of the roll, and the load applied to the top of the shoe, are two of the most important input parameters which can be controlled by an operator, for specific design conditions, all the calculated values were obtained at a function of these two parameters.

Figure 4 indicates that the clockwise deflection of the shoe increases with increasing speed at each fixed load and decreases as the load increases at any fixed speed. Note that at higher loads, the shoe becomes physically more stable, and its angular position becomes insensitive to the variation in applied load. The lubricant pressure distributions along the lengths of both subchannels for various applied loads and a roll speed of 1067 m/min are shown in figure 5. For all the operating conditions, the pressure distribution along the inside surface of the roll, is constant in the vicinity of each of the two respective sets of recesses, where lubricant enters the channel, and falls off monotonically as one moves from each recess towards the end of the subchannel fed by that recess. For all the operating conditions, the pressure exerted by the lubricant on the inner surface of the roll was slightly higher at the right-hand recess as compared with the left-hand recess; the pressure distribution in these regions has a significant effect on water removal during the wet pressing of paper. In general, the speed of the roll had only a small influence on the pressure distribution.

The results of the parametric study for the large shoe operating at a load of 1751 KN/m and at a roll speed of 610 m/min in which all the geometric and physical parameters except the oil viscosity were maintained fixed are shown in figures 6 and 7. Figure 6 corresponds to the influence of the oil viscosity in the range of 1-100 cp on the mechanical power and the total mass flow rate, and figure 7 corresponds to the influence of the oil viscosity on the lubricant thickness and the recess pressure. The mechanical power increased linearly with an increase in viscosity, however, the oil viscosity effected the mass flow rate in an non-linear fashion. An increase in oil viscosity from 1 cp to 10 cp resulted in a significant reduction in the mass flow rate, while an increase from 50 cp to 100 cp did not have any major influence in the flow. Figure 7 indicates that the right recess pressure and the leading edge thickness are directly proportional, and the left recess pressure and the trailing edge thickness are inversely proportional to the oil viscosity.

The results corresponding to angle of deflection for each shoe/roll configuration analyzed in this study indicate that operating such press rolls at higher loads will result in a more stable hydrostatic shoe, one in which the position of the shoe becomes relatively independent of the variation in the roll speed. This model can be used effectively to study the dependence of channel thicknesses, the deflection of the shoe, mass flow rates, pressure distributions, and the power required to operate the roll either on the applied load for a fixed roll speed or on roll speed for fixed load. Also, the model can be used to predict, for given applied loads and roll speeds, the effect that specific changes in design or physical parameters would have on lubricant thicknesses, angle of rotation of the shoe, mass flow rates, pressure distribution, and the mechanical power required to operate the roll; the mathematical model thus presents the engineer with what is anticipated to be an extremely effective tool for optimizing specific design factors in the construction of the shoe/roll configuration in impulse drying.

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FIGURES

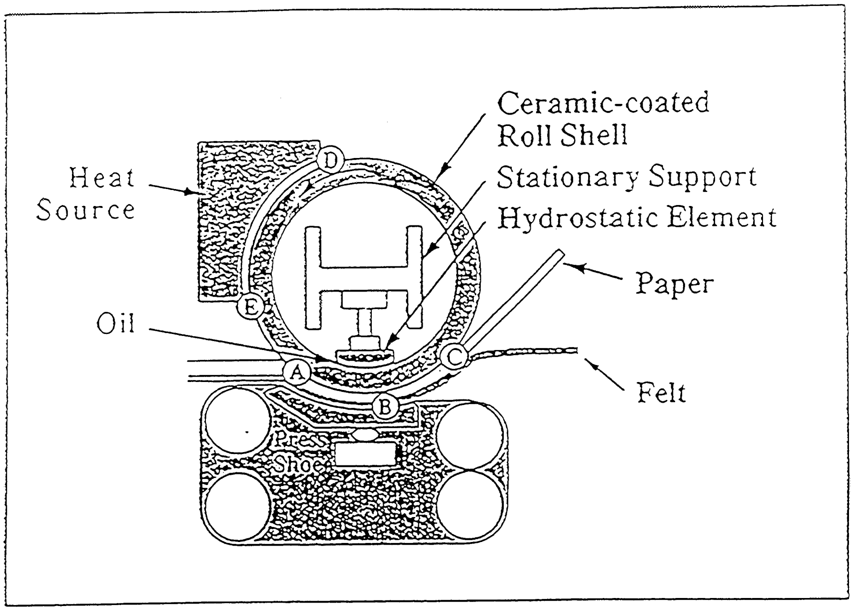

Figure 1. The Crown Compensated Impulse Drying Press Roll (not shown to scale).

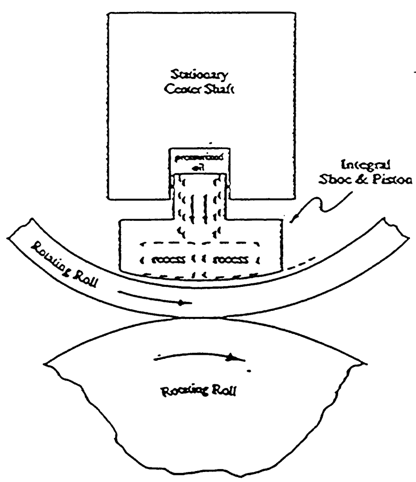

Figure 2. Cross sectional view of the shoe and the rotating shell.

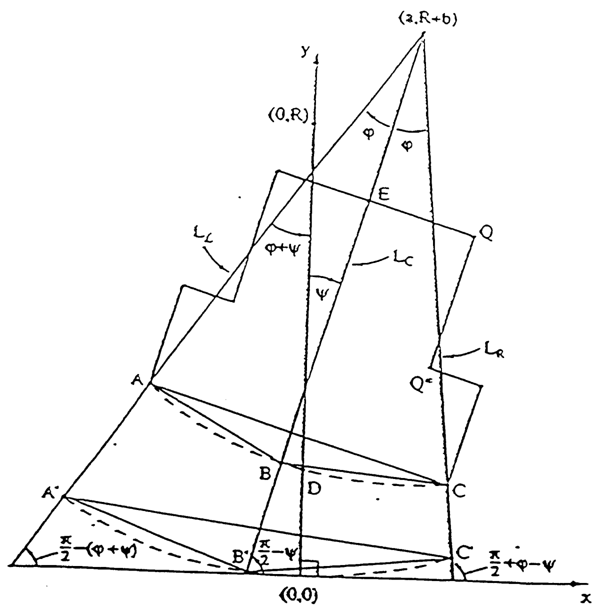

Figure 3. Motion of the hydrostatic shoe.

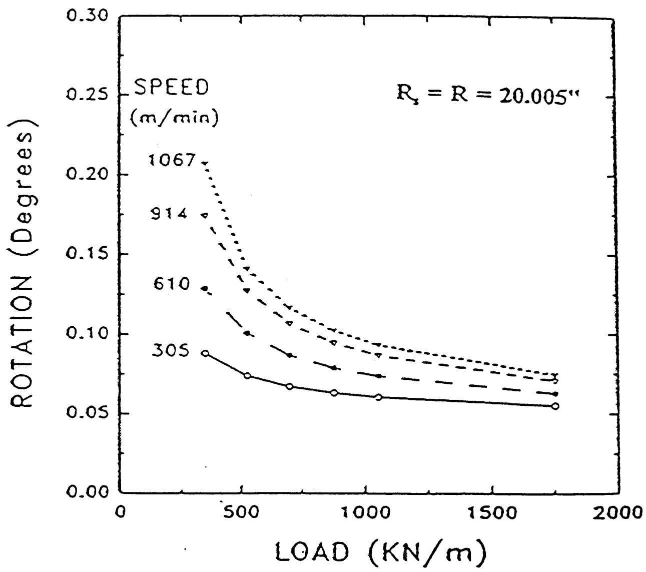

Figure 4. Predicted angle of rotation of the of the shoe vs. applied load.

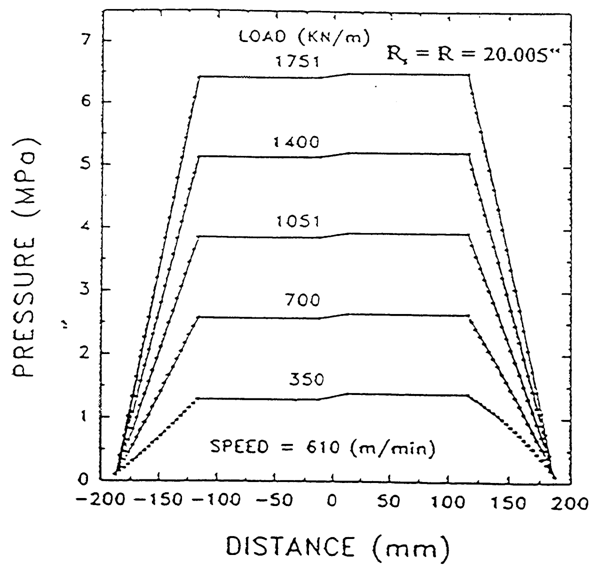

Figure 5. Predicted lubricant pressure distribution.

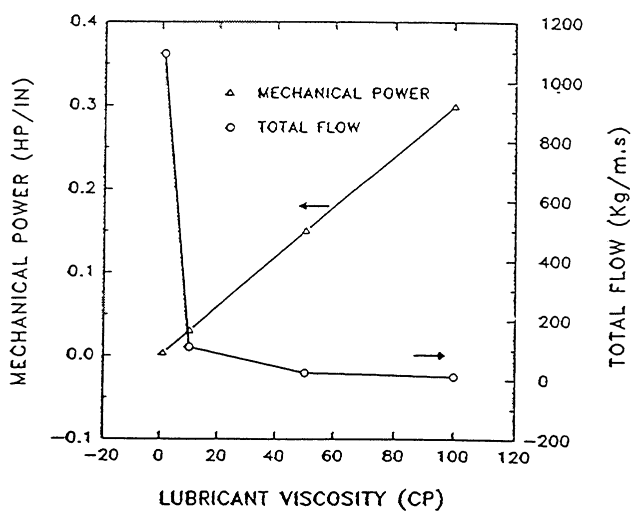

Figure 6. Influence of lubricant viscosity on mechanical power and mass flow rate.

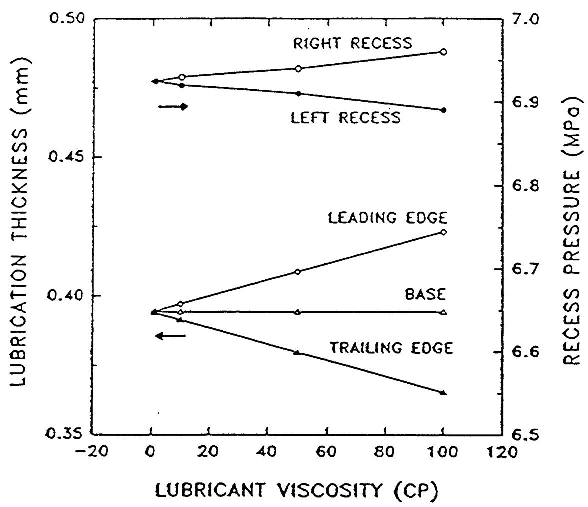

Figure 7. Influence of lubricant viscosity on its thickness and recess pressure.